

UAV-Relay-Assisted LEO Satellite Communication Systems with Cooperative Non-Orthogonal Multiple Access

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Abstract—This paper investigates the capacity performance of a low Earth orbit (LEO) satellite communication system assisted by a low-altitude unmanned aerial vehicle (UAV) acting as a relay. Specifically, the UAV employs cooperative non-orthogonal multiple access (NOMA) to forward signals, and the individual capacities of satellite-served users and ground base station-served users, as well as the total sum capacity, are analyzed. To eliminate cross-link interference, it is assumed that the frequency bands of the satellite-to-UAV link and the ground base station-to-UAV link are orthogonal. The UAV receives signals from both the satellite and the ground base station, and then simultaneously transmits them to the users by applying the NOMA transmission strategy. For validation, analytical expressions are derived and utilized to conduct Monte Carlo simulations. The simulation results confirm that the proposed scheme achieves a significantly higher sum throughput compared to conventional transmission schemes.

Keywords—UAV, Satellite, NOMA, Relaying

I. INTRODUCTION

Recently, continuous global efforts have been made to provide cellular services through low Earth orbit (LEO) satellite communications, with governments and private companies investing heavily in related research. In this context, international standardization bodies are actively developing standards for non-terrestrial networks (NTNs), which refer to communication infrastructures beyond terrestrial deployments. Among the various NTN technologies, LEO satellites and unmanned aerial vehicles (UAVs) have attracted significant attention, although their applications differ. The performance of LEO satellites varies depending on their specifications and size, but ongoing research aims to implement the full functionality of a gNB, thereby enabling LEO-based satellite communication systems with performance levels comparable to terrestrial gNBs. In contrast, UAVs offer greater versatility, with applications ranging from surveillance and reconnaissance to cargo delivery. More recently, UAVs have been investigated as relay nodes to

provide mobile communication services in areas where terrestrial coverage is unavailable [1].

Even for LEO satellites, the large distance of several hundred kilometers from the ground makes it challenging for terrestrial user terminals to reliably receive signals. Employing UAVs as relays for satellite signals is therefore a natural and promising solution. Furthermore, since satellites provide extremely wide coverage and serve a large number of users simultaneously, the use of non-orthogonal multiple access (NOMA) represents another important research direction. Consequently, various studies have explored UAV-assisted satellite systems employing NOMA. For instance, a unified analytical framework for hybrid satellite-UAV NOMA networks under realistic fading and imperfect channel state information (CSI) was developed in [2], where outage analysis, diversity characterization, and UAV relay optimization were presented. In [3], a reconfigurable intelligent surface (RIS)-aided NOMA-enabled space-air-ground integrated network (SAGIN) was proposed, introducing an alternating optimization framework for joint power allocation, RIS configuration, user association, and UAV trajectory design to enhance rate and energy efficiency. In the maritime communication scenario, [4] formulated a capacity maximization problem by jointly optimizing power allocation and UAV trajectory in a NOMA-enabled hybrid satellite-UAV-terrestrial network, proposing an iterative algorithm that improved system capacity by up to 33.3%. A low-complexity UAV grouping and power allocation algorithm for long-distance UAV networks using NOMA was introduced in [5], achieving approximately 19% higher capacity than orthogonal multiple access. In [6], a cluster-NOMA-enabled space-air-ground edge computing network (SAGECN) was studied, where multi-agent learning was applied for joint optimization of task offloading, resource allocation, and UAV trajectory, resulting in significant improvements in delay and spectrum efficiency. More recently, [7] developed a joint user

association, power allocation, and UAV trajectory (JUPT) optimization algorithm for NOMA-enabled SAG networks with satellite backhaul, demonstrating superior energy efficiency and rapid convergence.

Motivated by these works, this paper investigates the performance of a LEO satellite communication system assisted by a low-altitude UAV relay employing cooperative NOMA. Specifically, we analyze the individual and sum capacities of users served by the satellite and by a terrestrial base station (TN BS). The UAV aggregates the signals received from both the satellite and the TN BS using superposition coding and simultaneously forwards them to the users through cooperative NOMA transmission. The overall communication frame is divided into two phases. In the first phase, signals are transmitted from the satellite to the UAV, from the satellite to the satellite user, and from the TN BS to the UAV. In the second phase, the UAV forwards the aggregated signals to the users by applying the NOMA technique. The achievable rates of the users are employed as the performance metric.

To validate the effectiveness of the proposed scheme, analytical expressions are derived and used to conduct Monte Carlo simulations. The results show that the proposed method achieves superior sum throughput compared with schemes without UAV assistance and those without NOMA.

The remainder of this paper is organized as follows. Section II presents the system model, introduces the cooperative NOMA scheme, and provides the mathematical formulations. Section III discusses the simulation results and performance evaluation of the proposed scheme.

II. SYSTEM MODEL

In this paper, we consider an integrated terrestrial–satellite communication scenario as illustrated in Fig. 1, where both a LEO satellite and a terrestrial gNB (TN BS) provide services to ground terminals. The terminals may receive their desired signals either from the LEO satellite or from the terrestrial gNB. The LEO satellite serves terminals located within its coverage, and the users can access satellite services via the 3GPP NTN standard or the DVB standard. Due to the inherent characteristics of satellite communication, the received signals at the ground may be weak; thus, a UAV can be employed as a relay to improve the received signal quality. On the other hand, some users may receive services from the terrestrial gNB. However, when the users are geographically located outside the coverage of the TN BS, the UAV relay is also required. To eliminate cross-link interference, it is assumed that the frequency bands of the satellite-to-UAV link and the ground base station-to-UAV link are orthogonal.

We denote the user receiving signals from the satellite as UE1 and the user receiving signals from the terrestrial gNB as UE2.

The overall communication frame consists of two phases. In the first phase, the UAV receives signals from both the satellite and the terrestrial gNB. The UAV decodes and stores these signals; if decoding fails, the unsuccessfully decoded signal is not forwarded in the second phase. Meanwhile, UE1 also receives and stores the signal directly from the satellite. Since this signal may be too weak to decode successfully, UE1 simply stores it without decoding, and later combines it with the relayed signal in the second phase.

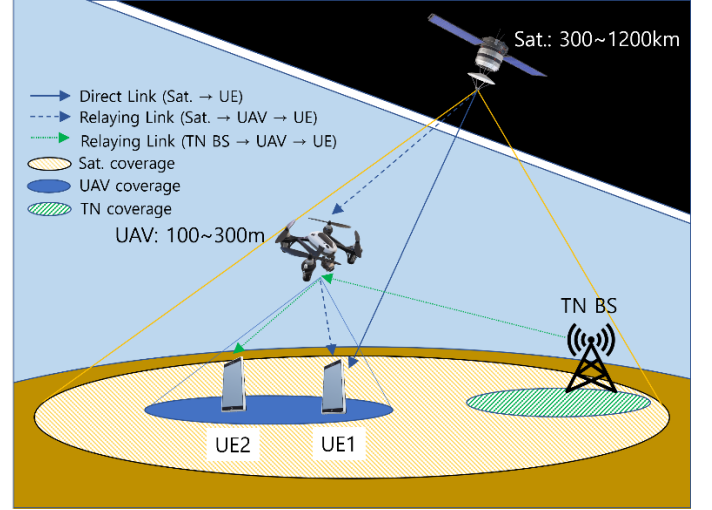


Figure 1. System Model

We denote the user receiving signals from the satellite as UE1 and the user receiving signals from the terrestrial gNB as UE2. The overall communication frame consists of two phases. In the first phase, the UAV receives signals from both the satellite and the terrestrial gNB. The UAV decodes and stores these signals; if decoding fails, the unsuccessfully decoded signal is not forwarded in the second phase. Meanwhile, UE1 also receives and stores the signal directly from the satellite. Since this signal may be too weak to decode successfully, UE1 simply stores it without decoding, and later combines it with the relayed signal in the second phase. Assume that the thermal noise at each node is AWGN with 0 mean and variance σ^2 .

The received signal at the UAV during the first phase is expressed as follows:

$$y_{UAV}^{sat} = h_{UAV}^{sat} \sqrt{P_{Sat}} x_1 + h_{UAV}^{BS} \sqrt{P_{BS}} x_2 + n_{UAV} \quad (1)$$

where h_{UAV}^{sat} is the channel coefficient between satellite and UAV, h_{UAV}^{BS} is the channel coefficient between satellite and TN BS, P_{Sat} is the transmit power of the satellite, P_{BS} is the transmit power of TN BS, x_1 is the desired symbol for UE1 with normalized power, x_2 is the desired symbol for UE2 with normalized power, and n_{UAV} is the AWGN at the UAV, respectively.

The received signal at UE1 during the first phase is expressed as follows:

$$y_{UE1}^{sat} = h_{UE1}^{sat} \sqrt{P_{Sat}} x_1 + n_{UE1} \quad (2)$$

where h_{UE1}^{sat} is the channel coefficient between the satellite and UE1 and n_{UE1} is the AWGN at the UE1, respectively.

In the second phase, the UAV forwards the successfully decoded signals to UE1 and UE2 by applying the cooperative NOMA scheme. The received signals at UE1 and UE2 in the second phase are given by:

$$y_{UE1}^{UAV} = g_{UE1}^{UAV} \sqrt{P_{UAV}} (\sqrt{\alpha_1} x_1 + \sqrt{\alpha_2} x_2) + n_{UE1} \quad (3)$$

$$y_{UE2}^{UAV} = g_{UE2}^{UAV} \sqrt{P_{UAV}} (\sqrt{\alpha_1} x_1 + \sqrt{\alpha_2} x_2) + n_{UE2} \quad (4)$$

where g_{UE1}^{UAV} is the channel coefficient between UAV and UE1, g_{UE2}^{UAV} is the channel coefficient between UAV and UE2, P_{UAV} is the transmit power of the UAV, $\alpha_i, i \in \{1, 2\}$, $\alpha_1 + \alpha_2 = 1$ is the power allocation coefficient for UEi and n_{UE2} is the AWGN at UE2 respectively.

For NOMA transmission, the UAV allocates its transmit power between UE1 and UE2. It is assumed that the power allocated to UE1 is smaller than that allocated to UE2, i.e., $\alpha_1 < \alpha_2$, which is a basic principle of NOMA. Accordingly, UE1 first decodes UE2's signal and applies successive interference cancellation (SIC) before decoding its own signal, while UE2 treats the signal intended for UE1 as noise and directly attempts to decode its own signal. For the sake of simplicity, we assume that UE1 always succeeds in decoding the signal intended for UE2.

Finally, the achievable rates of UE1 and UE2 are given by

$$C_{UE1} = \frac{1}{2} \log_2 \left(1 + \frac{|h_{UE1}^{sat}|^2 P_{Sat} + |g_{UE1}^{UAV}|^2 \alpha_1 P_{UAV}}{\sigma^2} \right), \quad (5)$$

$$C_{UE2} = \frac{1}{2} \log_2 \left(1 + \min \left(\frac{|h_{UAV}^{BS}|^2 P_{BS}}{\sigma^2}, \frac{|g_{UE2}^{UAV}|^2 \alpha_2 P_{UAV}}{|g_{UE2}^{UAV}|^2 \alpha_1 P_{UAV} + \sigma^2} \right) \right) \quad (6)$$

respectively, and the sum-rate is given by

$$C_{Sum} = C_1 + C_2. \quad (7)$$

III. SIMULATIONS

For the simulations, the system parameters are set as follows. The channels from the satellite to the UAV and from the satellite to UE1 are modeled as shadowed Rician fading channels, where the average shadowing parameters $b = 0.126$, $m = 10.1$, $\Omega = 0.835$ [8] are adopted. The channels between the UAV and UE1, the UAV and UE2, and the TN BS and UAV are modeled as Rician fading channels which are assumed to have unit average power ($\Omega=1$), and the Rician K-factor is set to 5 dB to

represent a moderate LOS environment. The altitude of the satellite is assumed to be 600 km, the distance between the UAV and the terminals is set to 300 m, and the distance between the TN BS and the UAV is set to 10 km. The transmit power of the satellite is adjusted such that the received power at both the UAV and the terminals is fixed at -100dBm. The transmit powers of the UAV and the TN BS are assumed to be in the range of 40–46 dBm.

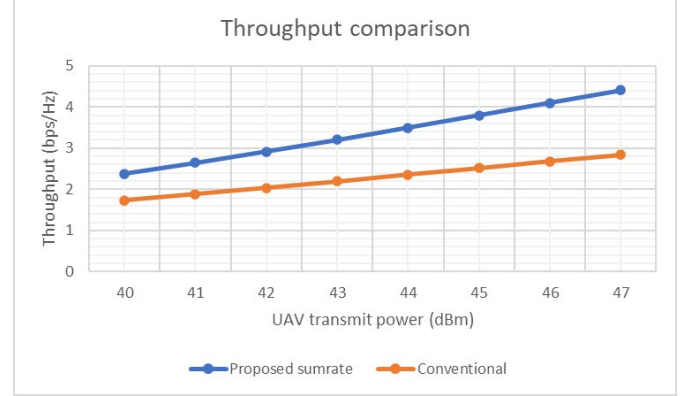


Figure 2. Throughput comparison

As shown in Fig. 2, the proposed scheme achieves a significantly higher sum throughput compared to the conventional scheme without NOMA. This performance gain is mainly attributed to the fact that the proposed cooperative NOMA transmission allows the UAV to simultaneously forward the signals of both users, thereby improving the spectral efficiency. In contrast, the conventional orthogonal transmission strategy allocates separate resources for each user, which results in lower overall throughput. These results clearly demonstrate the effectiveness of integrating UAV relaying with NOMA in enhancing the system capacity of integrated terrestrial-satellite networks.

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